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RESEARCH ARTICLE

Vulnerability of Eastern Tropical Pacific chondrichthyan fish to climate change

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Abstract

Climate change is an environmental emergency threatening species and ecosystems globally. Oceans have absorbed about 90% of anthropogenic heat and 20%–30% of the carbon emissions, resulting in ocean warming, acidification, deoxygenation, changes in ocean stratification and nutrient availability, and more severe extreme events. Given predictions of further changes, there is a critical need to understand how marine species will be affected. Here, we used an integrated risk assessment framework to evaluate the vulnerability of 132 chondrichthyans in the Eastern Tropical Pacific (ETP) to the impacts of climate change. Taking a precautionary view, we found that almost a quarter (23%) of the ETP chondrichthyan species evaluated were *highly* vulnerable to climate change, and much of the rest (76%) were *moderately* vulnerable. Most of the *highly* vulnerable species are batoids (77%), and a large proportion (90%) are coastal or pelagic species that use coastal habitats as nurseries. Six species of batoids were *highly* vulnerable in all three components of the assessment (exposure, sensitivity and adaptive capacity). This assessment indicates that coastal species, particularly those relying on inshore nursery areas are the most vulnerable to climate change. Ocean warming, in combination with acidification and potential deoxygenation, will likely have widespread effects on ETP chondrichthyan species, but coastal species may also contend with changes in freshwater inputs, salinity, and sea level rise. This climate-related vulnerability is compounded by other anthropogenic factors, such as overfishing and habitat degradation already occurring in the region. Mitigating the impacts of climate change on ETP chondrichthyans involves a range of approaches that include addressing habitat degradation, sustainability of exploitation, and species-specific actions may be required for species at higher risk. The assessment also highlighted the

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need to further understand climate change's impacts on key ETP habitats and processes and identified knowledge gaps on ETP chondrichthyan species.

KEYWORDS
batoid, chimaera, ecological risk assessment, elasmobranch, ETP, shark

1 | INTRODUCTION

Climate change is now recognized as an urgent global environmental issue impacting many marine biodiversity hotspots and economically important marine resources (Pörtner et al., 2019). The earth's surface has warmed by 0.6°C over the past 100 years and a further 1.0–3.7°C increase is expected by 2100, with larger changes projected under high carbon dioxide (CO_2) emissions scenarios (Cheng et al., 2020; IPCC, 2018). Ocean warming has been identified as a primary determinant of species range shifts (e.g., Pinsky et al., 2020) and, in combination with oxygen, constrains the metabolic limits of marine organisms (Deutsch et al., 2015). Warming strengthens upper ocean stratification, inhibiting the supply of nutrients to the euphotic zone as well as the resupply of oxygen to deeper waters (Capotondi et al., 2012; Kwiatkowski et al., 2020). The accumulation of atmospheric CO_2 underlying much of observed global warming also acidifies the ocean (Orr et al., 2005), which can have detrimental effects on shell-forming species and other organisms (Kroeker et al., 2013). Changes in upwelling and nutrient availability will impact primary productivity, resulting in productivity declines that may threaten food availability (Kislik et al., 2017; Rykaczewski et al., 2015). Projections of these potential “ocean stressors” for the end of the 21st century suggest that they will continue to pose challenges, even under aggressive mitigation strategies (John et al., 2015; Kwiatkowski et al., 2020) and these effects would continue beyond 2100. There is therefore an urgent need to better understand the impact of such stressors on marine species and key habitats to inform adaptive management strategies.

The Eastern Tropical Pacific (ETP) is located between the subtropical gyres of the North and South Pacific; eastern boundary currents flow into the ETP from the north (California Current) and south (Peru or Humboldt Current), while also containing the eastern end of the Pacific equatorial current system and the eastern Pacific warm pool (Lavín et al., 2006). It has a frontal zone over the Pacific Ocean, and many upwellings zones throughout the region (Forryan et al., 2021; Lluch-Cota, 1999; Willett et al., 2006). The upwelling off the Baja peninsula spans almost one quarter of the equatorial circumference generating the highest average air-to sea heat fluxes and one quarter of global new primary production (Eisele et al., 2021; Lavín et al., 2006; Ryan et al., 2017). Additionally, the Humboldt current reaches close to the equator, where persistent upwelling also results in higher fish production (Ryan et al., 2017). The oceanography of ETP is also characterized by a shallow thermocline (at around 25 m), high surface chlorophyll concentrations (down to about 50 m) and oxygenation profiles showing hypoxic conditions below the thermocline (Prince & Goodyear, 2006). These features are strongly impacted by the El Niño Southern Oscillation (ENSO), which generates large-scale fluctuations in temperature and other ocean properties in the ETP every 5–10 years (Mantua et al., 1997; Newman et al., 2016; Wang & Fiedler, 2006). Changes in the strength and frequency of ENSO events are uncertain but possible under climate change (McPhaden et al., 2020).

The ETP has geological structures such as oceanic islands and seamounts that interact with ocean circulation and migratory species are known to regularly move among them and mainland creating marine corridors throughout the ETP (Cerutti-Pereyra et al., 2022; Klimley et al., 2022; Lara-Lizardi et al., 2020). Furthermore, the ETP coast includes sandy flats, coastal bays, estuaries, and mangrove forests that provide nursery areas for many species (Castellanos-Galindo et al., 2013; López-Angarita et al., 2016; Miloslavich et al., 2011). Such variety of oceanic features, geological structures, and coastal habitats, results in a highly productive region that provides the basis for a complex marine food structure and biodiversity hotspots that support artisanal and industrial fisheries (Hearn et al., 2010; Klimley et al., 2022; Ryan et al., 2017).

Notably, the ETP also has one of the highest levels of endemism and significant concentrations of marine megafauna biodiversity worldwide, including chondrichthyans (sharks, batoids, and chimaeras) which play key ecological roles in marine ecosystems as one of the largest groups of predatory species connecting food webs across ecosystems (Heithaus et al., 2008; Heupel et al., 2014). Notably, this group is economically important globally through fisheries and tourism (Dent & Clarke, 2015; Gallagher & Hammerschlag, 2011). It is a key component of targeted and non-targeted catch in both artisanal and industrial fisheries in the ETP (Cerutti-Pereyra et al., 2019; Croll et al., 2016; Martínez-Ortiz et al., 2015) and they have become an important economic tourism activity (Cisneros-Montemayor et al., 2020; Lynham et al., 2015; Topelko & Dearden, 2005). Notably, chondrichthyans are one of the most threatened marine groups globally due to overfishing (Dulvy et al., 2021; Pacoureau et al., 2021; Sherman et al., 2023) and other threats such as climate change may aggravate the status of their depleted populations (Carrier et al., 2022; Hazen et al., 2013; Pereira Santos et al., 2021). Despite the important ecological and economic roles, little is known about the impacts of climate change on chondrichthyans and how they may respond to such changes.

Ecological risk assessments (ERAs) investigate the effects of ‘ecological hazards’ and determine how an ecological asset will be affected by the identified threat (Hobday, Smith, et al., 2011). Such assessments are helpful to evaluate the overall risk and impacts faced particularly by data-poor species, such as many chondrichthyan species (Chin et al., 2010; McClure et al., 2023; Walker et al., 2021). This risk assessment has evolved in the last decade into an 'integrated risk assessment' that evaluates climate change vulnerability and predicts species' resilience to inform adaptation policy. For example, suggestions such as protecting spawning biomass or nursery areas, which might increase stock resilience or decrease fishing mortality on high-risk species can contribute to the sustainable management of those species, or managing habitats or areas as refuges for vulnerable (VU) species (Foden et al., 2013; Hare et al., 2016; Quinlan et al., 2023). The integrated risk assessment presented here provides an initial assessment of the vulnerability of ETP chondrichthyans to climate change, a better understanding of the relationship between climate change and its consequences, and a proposed framework for research and management prioritization. This study has also a report in Spanish available on the Charles Foundation website (Cerutti-Pereyra et al., 2024a).

2 | MATERIALS AND METHODS

The integrated risk assessment involves three steps (Table 1): (1) Defining the assessment context, (2) assessing components of vulnerability, and (3) integrating vulnerability components to derive the overall score of vulnerability of each species to the threat of climate change (Chin et al., 2010).

2.1 | Defining the assessment context

2.1.1 | Study region

For the purposes of this study, the ETP was defined as the region from the Gulf of California and the southern tip of the Baja peninsula, Mexico (tropic of Cancer) in the north, to the border between Ecuador and Peru in the south (Figure 1). The westernmost limit is defined at 120°W (western limit of El Niño zone 3, NCAR, 2022). A broad description of the ETP's oceanographic features, geological structures, and coastal habitats is provided in the Section 1.

2.1.2 | Participants

The assessment was conducted by an expert panel of 19 scientists from eight countries (listed as coauthors) that had specific local and regional expertise on regional habitats and ecosystems, chondrichthyan and deep-sea species biology and ecology, shark physiology, risk assessments, and climate change/oceanography. The panel of experts contributed to the data gathering, climate change discussions, and species' assessments through virtual workshops held during 2020 and 2021. Discussion continued until there was a consensus on the assessment for each species.

TABLE 1 Overview of the risk assessment for climate change for chondrichthyans in the Eastern Tropical Pacific.

Step	Procedure
1. Context	*Define the entity to be assessed*
	Spatial (study site) and temporal (projections) scope defined. Species lists compiled, species data collected in a database, and species organized into ecological groups
	Define climate change factors
	Climate change factors identified for the region. Projections calculated to 2100. Literature review and experts' inputs to identify predicted impacts on the environment, habitats, and processes
	Define vulnerability attributes
	Biological and ecological traits defined for each species sensitivity and adaptive capacity
2. Assessment	*Ranking exposure*
	Exposure of each species to each climate change factor was ranked as low, medium, or high
	Ranking sensitivity and adaptive capacity
	Each attribute of sensitivity (maximum size, size at maturity, productivity, longevity, and rarity) and adaptive capacity (latitudinal range, habitat specificity, mobility, trophic specificity, and physiological tolerance) was ranked as low, medium, or high for each species to derive the overall vulnerability for each component
3. Integration	*Integrate vulnerability components*
	Matrix used to integrate the rankings of all components (exposure, sensitivity, and adaptive capacity) to derive overall vulnerability of each species to each climate change driver
	Collate rankings
	Species rankings collated to derive the vulnerability of each ecological group to climate change
	Synergies, interactions, and knowledge gaps
	Identify potential synergies and interactions with non-climate change issues and identify knowledge gaps arising

2.1.3 | Units of analysis and ecological groups

Information and species profiles for 132 species of chondrichthyans (i.e., 65 sharks, 60 batoids, and 7 chimaeras) were collated from published and unpublished literature/data, the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species (https://www.iucnredlist.org/) available until 2022, as well as expert panels' inputs. The data used to derive the rankings for this study are openly available in Zenondo at https://doi.org/10.5281/zenodo.11218757 (Cerutti-Pereyra et al., 2024b) and the reference list available in the Supporting Information. To facilitate habitat-specific assessments and the presentation of results, we divided the 132 chondrichthyan species found for the ETP into four discrete ecological groups based on those used by

Chin et al. (2010) and the concept of ecomorphotypes postulated by Compagno (1990) (Table 2). Many species appeared in more than one ecological group and were therefore considered in all ecological groups such species was present.

2.1.4 | Climate change factors

Seven climate change factors were identified by the expert panel: ocean warming, deoxygenation, acidification, changes in primary

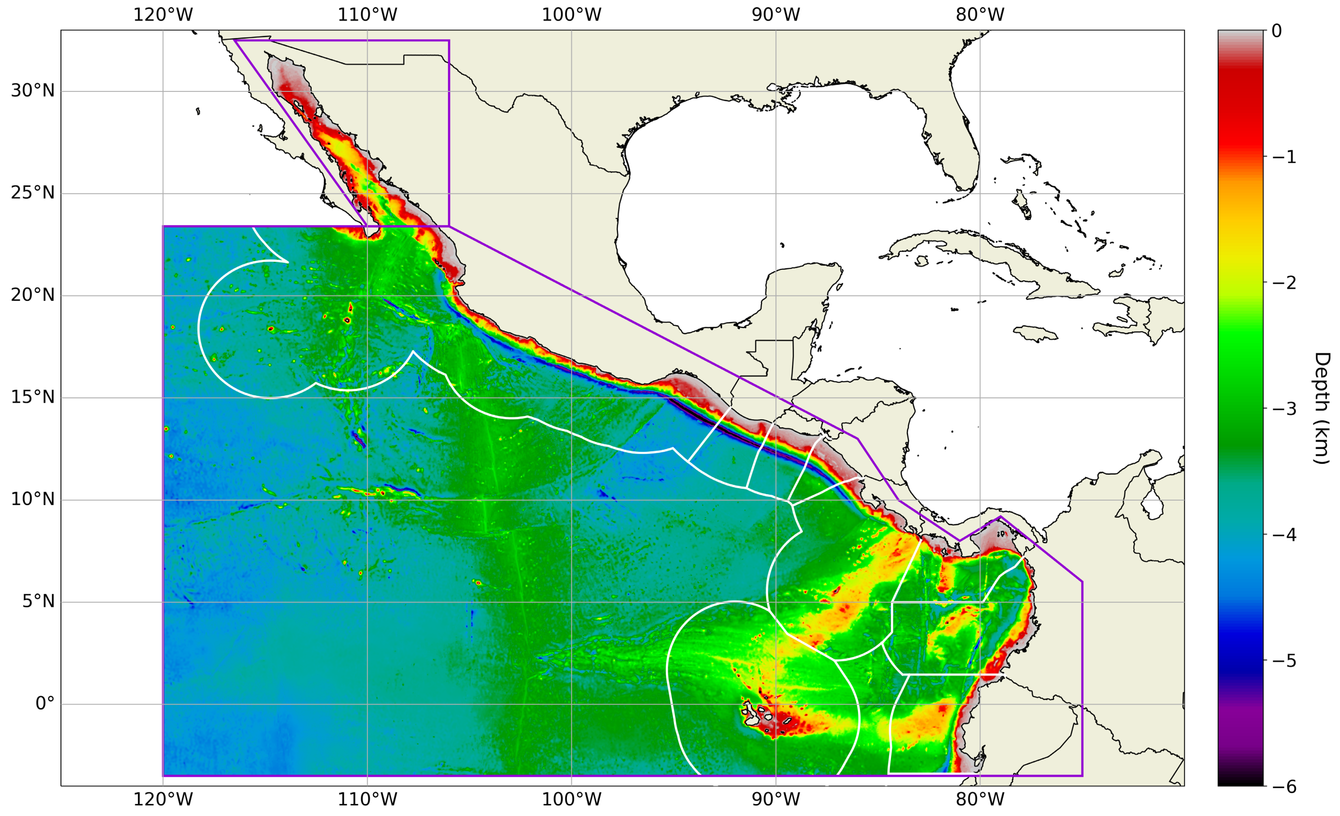

FIGURE 1 Eastern Tropical Pacific study region (outlined in purple and not depicting accepted national boundaries) including oceanic islands, bathymetry, and countries' Exclusive Economic Zone boundaries (white line).

TABLE 2 Description of the four ecological groups of Eastern Tropical Pacific (ETP) chondrichthyans used in the integrated risk assessment. Some species are in more than one ecological group.

Ecological group	Definition	Number of species	Examples of species
Coastal (freshwater, estuarine, and inshore)	Include species that are commonly found in freshwater (e.g., rivers), estuaries, shallow bays, mangroves, intertidal seagrass beds, foreshores, and mudflats, inshore fringing reefs, shallow coastal waters, rocky shoals, sponge gardens and habitats extending from coastal inter-tidal habitats to the mid-shelf platform or ribbon reefs to 40 m depth	98	Pacific Eagle Ray (*Aetobatus laticeps*), bull shark (*Carcharhinus leucas*)
Shelf	Include species that use deeper water and seabed habitats, extending to the continental slope edge. For the ETP, it will include waters from the surface to the isobath of 500 m, including deep-water benthic habitats and the platform around oceanic islands of the ETP	90	Arctic skate (*Amblyraja hyperborea*), prickly shark (*Echinorhinus cookei*)
Bathyal	Include species that use benthic habitats of the continental slope and bond, extending down to 2000 m depth	42	Deepsea skate (*Bathyraja abyssicola*), whitespot ghostshark (*Hydrolagus alphus*)
Pelagic	Include species generally found in depths less than 200 m above continental slope and plain, the water column, and open ocean waters	52	Spinetail mobula (*Mobula japanica*), blue shark (*Prionace glauca*)

productivity, changes in freshwater inputs, changes in salinity, and sea level rise. These factors, which are similar to those considered in risk assessments (e.g., Chin et al., 2010), may impact chondrichthyans' physiology, habitat use, ecological interactions, and the food webs directly linked to them (Table S1). We anticipated that the last three factors (changes in freshwater inputs, salinity, and sea level rise) were only relevant for coastal ecosystems.

Projections for changes in ETP ocean temperature, salinity, dissolved oxygen concentration, pH, and productivity were calculated from earth system model (ESM) contributions to the Sixth Coupled Model Intercomparison Project (Eyring et al., 2016), specifically those for the highest greenhouse gas emissions and radiative forcing scenario, SSP5-8.5 (O'Neill et al., 2014). While a net increase in radiative forcing of 8.5 watts m-2 would be achieved through emissions of a combination of multiple greenhouse gases (e.g., CO_2, methane, nitrous oxide, fluorinated gases) and aerosol emissions (Pathak et al., 2022), the SSP5-8.5 marker is generally associated with CO_2 emissions of ~120 GtCO_2 by the end of the century and atmospheric CO_2 levels ~1000 ppm (O'Neill et al., 2016; Riahi et al., 2017). Changes were calculated as the difference between 30-year mean climatological states: future (2071–2100)–historical (1985–2014), in the Pacific region bounded by 23.5 N to 3 S and 120 W to 75 W. These calculations did not include the Gulf of California, which is not adequately resolved in coarse resolution ESMs (Asch et al., 2016). We report the range of model mean changes across models in S1, along with the associated level of confidence/consensus in sign and magnitude of the change (see Table S1). Projections of change in precipitation and sea level over the study area and adjacent South and Central American landmasses were taken from Oppenheimer et al. (2019) and Tebaldi et al. (2021), respectively.

2.1.5 | Vulnerability components and attributes

The risk assessment used three components to evaluate climate change vulnerability: *exposure*, *sensitivity*, and *adaptive capacity* (Chin et al., 2010; Jones & Cheung, 2017; Walker et al., 2021).

Exposure was assessed by comparing the overlap of a species' distribution and habitat use within the study area (i.e., coastal vs. offshore, pelagic vs. bathyal) with projected changes in each climate change factor. *Exposure* thus aligns primarily with coast to open ocean and surface to depth gradients in projected changes. For example, exposure to ocean warming attenuates in deeper habitats where less warming is projected to penetrate over the next century and exposure to changes in salinity, freshwater inputs, and sea level are expected to be most acute in coastal regions and attenuated offshore. *Exposure* is considered a 'negative' component: the higher the exposure, the greater the species' vulnerability to climate change. The evaluation of *Exposure* included all habitats within the distribution of each species.

Sensitivity included inherent life-history traits that an individual cannot alter through behavioral or physiological adaptation, and comprised five attributes: maximum size, size at maturity, productivity (litter size divided into pups and eggs), longevity, and rarity. Chondrichthyan biology suggests that large sizes, low productivity, long life spans, and rarity confer higher sensitivity to a threat (Cailliet et al., 2005; Field et al., 2010; Musick et al., 2000). Just as the component of *exposure*, *sensitivity* is also a 'negative' component where high sensitivity equates to increased potential impact from the threat. Sizes (maximum and at maturity) of sharks and shark-like bodied batoids (e.g., guitarfish) were defined using total length (TL, measured from the snout to the tip of the caudal fin); for the rest of batoids it was based on disc width (DW, measured between the furthest points of the pectoral fins). Size at maturity was calculated as a proportion of maximum size rather than an absolute value (Mejía-Falla et al., 2019). The attribute of rarity encompasses the species, population the size, and rebound potential (see Chin et al., 2010).

Adaptive capacity is considered a 'positive' component. High adaptive capacity means that a species can change its behavior to accommodate changing environmental conditions as a result of acclimation or compensation allowing a species to survive in new conditions. This component comprised five attributes: latitudinal range, habitat specificity, mobility (or immobility), trophic specificity (diet), and physiological tolerance. Larger ranges, generalist habitat use and diet, mobility and physiological tolerance confer higher adaptability. Latitudinal range included the central and eastern Pacific Ocean (distributions in the Western Pacific Ocean were not included in the analysis). Habitat specificity included the records of coastal nurseries for each species; if a species was recorded to use coastal nurseries, its sensitivity was increased (i.e., habitat requirements were more rigid). Mobility included records of both horizontal and vertical movements and migrations.

2.2 | Assessment and integration

The level of *exposure*, *sensitivity*, and *adaptive capacity* were ranked as *low*, *moderate*, or *high*, based on the information available and experts' judgement for each species for each attribute. After ranking all attributes for all species, a logic rule of the majority (hereafter referred to as the majority rule) was used to derive the final rank for each component: the ranking held by most attributes was taken as the final rank for that component while *moderate* was assigned in case of a tie. For example, if the five attributes of *sensitivity* were ranked as H, H, L, L, H, this component would be ranked as H, which reflects the ranking of the majority of these attributes. Instead, if it had a tie of H, H, L, L, M, this component then would be ranked as M, which reflects the variety of rankings without a majority. Because *adaptive capacity* is a positive component, we defined "*rigidity*" as the inverse of adaptive capacity for purposes of the vulnerability calculation, that is, species with low *adaptive capacity* are assigned a high *rigidity*, which favors a high vulnerability ranking. The term *rigidity* is used from now onwards for this component.

Once all attributes and components for each species were ranked (Tables S2–S4), the rankings were combined using the 'majority rule' to produce a matrix integrating the three components and calculating the overall vulnerability of each chondrichthyan species (Table S5). Once all vulnerability components for the 132 species were assessed, they were collated in ecological groups to determine the relative vulnerability of each group. Rankings for all species were reviewed by the expert panel individually and during online workshops held in 2021. We also present results of species' vulnerability in relation to the IUCN categories. Tables S2–S6 are openly available in Zenondo at https://doi.org/10.5281/zenodo.11278035 (Cerutti-Pereyra et al., 2024c).

2.2.1 | Uncertainty and the precautionary principle

Uncertainty in the information needed to rank each attribute was managed through two approaches. First, when species-specific data were not found for a given species, we used information from a 'sister species' (same genus). This was noted throughout the database because assessing a species' vulnerability based on sister species data may lower the confidence in the results. Therefore, those species where ≥50% of the information used for the assessment was sourced from a sister species are considered to have 'low' confidence. The second approach invoked the precautionary principle: if there was no information available at all for a particular attribute, it was ranked as *high*, which is consistent with the precautionary principle widely used in ERAs to recognize that lack of information increases risk (Chin et al., 2010; Hobday, Game, et al., 2011).

3 | RESULTS

Through the risk assessment, we identified (1) the vulnerability of 132 species of chondrichthyans to climate change in the ETP, and (2) the linkages between exposure of these species and ecological groups to climate change factors. We then suggest management actions addressing the risks identified.

3.1 | Vulnerability of ETP chondrichthyans

From the total number of *sharks* ($n=65$), 11% had an overall *high* vulnerability to climate change, 88% had *moderate* vulnerability, and 1% had *low* vulnerability (Figure 2a). From the total number of *batoids* ($n=60$), 38% had an overall *high* vulnerability and 62% had *moderate* vulnerability (Figure 2a). All *chimaeras* ($n=7$) had *moderate* vulnerability to climate change (Figure 2a). Overall, 23% ($n=30$) of ETP chondrichthyans were ranked with *high* vulnerability (Table 3), most of which were batoids (24 batoids and 6 sharks), and five of these species with *high* vulnerability also had low confidence. Meanwhile, 76% ($n=101$) of ETP chondrichthyans were ranked with *moderate* vulnerability (57 sharks, 37 batoids, 7 chimaeras), over half of which were sharks, and 11 of these 101 species had lower confidence. Only 1% (one species of shark, *Isistius brasiliensis*) was ranked with *low* vulnerability, but had high confidence (Table S5). Six species of batoids (*Aetomylaeus asperrimus*, *Beringraja cortezensis*, *Hypanus longus*, *Pristis pristis*, *Styracura pacifica*, and *Urotrygon simulatrix*) had *high* vulnerability in all three components and only one species of shark (*Isistius brasiliensis*) had an overall *low* vulnerability in all three components (Table S5).

3.2 | Rankings of components

Of those species with *high* vulnerability ($n=30$), 20% had *high* ranks on all three components, 87% had *high* exposure, 60% had *high* sensitivity, and 73% had *high* Rigidity (i.e., low adaptive capacity). Of the 101 species with *moderate* vulnerability to climate change, 11% were had *moderate* ranking on all three components, 54% had *high* exposure to climate change, 11% had *high* sensitivity, and 3% had *high* rigidity (Table S5).

The component of exposure had the highest number of ETP chondrichthyan species with a *high* ranking (H: 62%, M: 24%, L: 14%). The primary component that increased a species' exposure ranking was the use of coastal habitats and nurseries, where exposure to widespread climate drivers such as ocean warming, acidification, and changing oxygen was compounded by the exposure to changes in salinity, freshwater inputs, and sea level rise (Figure 3). The component of sensitivity (H: 22%, M: 74%, L: 4%) had the highest number of species with a *moderate* ranking. From the *low* rankings, rigidity had the highest number of all three components (Figures 2b and 4).

Over 60% of species were found to have *high* exposure on five of the seven climate change factors used in this assessment. For the factor of 'changes in productivity', most species (95%) were ranked with *moderate* exposure, and for three factors (changes in freshwater inputs, changes in salinity, and sea level) 29% of species ranked with *low* exposure. When examining how the ranking of individual climate change factors contribute to a species' vulnerability, 69% of 132 ETP chondrichthyan species were ranked with *high exposure* to 'ocean warming' (Figures 2c and 4). Meanwhile, 'deoxygenation' and 'acidification' were also assessed as affecting a large number of species, with 64% of species ranked with *high* exposure to the former and 61% of species were ranked with *high* exposure to the latter. Only, 5% of species were ranked with *high* exposure to 'changes in productivity' and 95% with *moderate* exposure to this factor. For coastal species, both factors 'changes in freshwater inputs' and 'changes in salinity' had 61% species ranked with *high* exposure, while 59% were ranked with *high* exposure to 'sea level rise' (Figures 2c and 3; Table S6).

3.3 | Vulnerability of threatened ETP chondrichthyans to climate change

According to the IUCN Red List of Threatened Species (https://www.iucnredlist.org/), of the 132 ETP chondrichthyan species, 9%

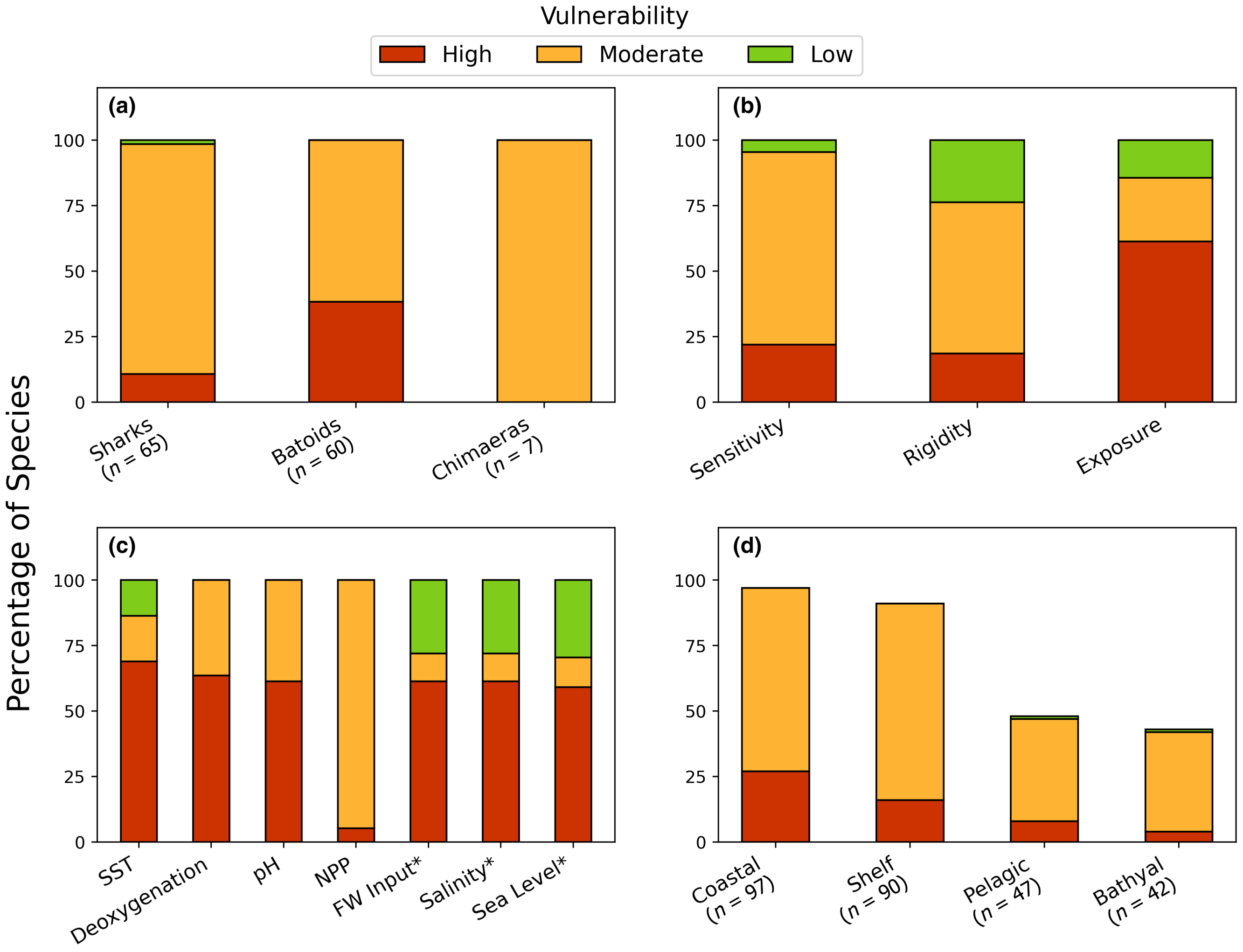

FIGURE 2 Proportion of sharks, batoids, and chimaeras by vulnerability (a), proportion of overall vulnerability by component (b), by climate change factor (c) (*only assessed for coastal ecological group, NPP, Net primary productivity, FW, Freswhater; SST, Sea surface temperature), and by ecological group (d).

are listed as Critically Endangered (CR), 11% as Endangered (EN), 27% as Vulnerable (VU), 14% as Near Threatened (NT), 32% as Least Concern (LC), and 7% as Data Deficient (DD) (Figure S1; Table S5).

From those ETP chondrichthyan species listed as CR and EN ($n=27$), 26% (five batoids, two sharks) had an overall *high* vulnerability to climate change, while 74% (six batoids, 14 sharks) had an overall *moderate* vulnerability. From those 36 ETP chondrichthyan species listed as VU, 27% (six batoids, four sharks) had an overall *high* vulnerability to climate change, while 69% (12 batoids, 12 sharks, one chimaeras) had *moderate* vulnerability, and 2.7% (one shark) had *low* vulnerability.

From 18 ETP chondrichthyan species listed as NT, 28% (five batoids) had an overall *high* vulnerability to climate change, while 72% (seven batoids, four sharks, and two chimaeras) had *moderate* vulnerability. From 42 ETP chondrichthyan species listed as LC, 14% (five batoids, one shark) had an overall *high* vulnerability to climate change, while 86% (nine batoids, 23 sharks, and four chimaeras) had *moderate* vulnerability.

Finally, of the nine ETP chondrichthyan species listed as DD, 22% (two batoids) had an overall *high* vulnerability and 78% (three batoids and four sharks) had *moderate* vulnerability to climate change (Table S5; Figure S1).

4 | DISCUSSION

This integrated risk assessment provides an important reference point for the vulnerability of 132 chondrichthyans in the ETP to climate change based on current understanding of each species' attributes, the projected changes in the ETP to the end of the 21st century, and the exposure of each species. Overall, our results indicate that 23% of ETP chondrichthyan species exhibit *high* vulnerability and 76% exhibit *moderate* vulnerability to climate change. Importantly, we found that 77% of ETP chondrichthyans exhibiting *high* vulnerability to climate change are batoids. Understanding the extent to which climate change can affect a species and the factors

TABLE 3 Eastern Tropical Pacific chondrichthyan species most vulnerable to climate change (have *high* overall vulnerability).

Ecological group(s)	Family	Species name	Common name	IUCN
Coastal	Aetobatidae	*Aetomylaeus (Pteromylaeus) asperrimus*	Roughskin bull ray	DD
Coastal	Narcinidae	*Diplobatis ommata*	Pacific dwarf numbfish	LC
Coastal	Narcinidae	*Narcine leoparda*	Leopard numbfish	VU
Coastal	Pristidae	*Pristis pristis*	Largetooth sawfish	CR
Coastal	Potamotrygonidae	*Styracura pacifica*	Pacific chupare	VU
Coastal	Urotrygonidae	*Urobatis tumbesensis*	Tumbes round stingray	LC
Coastal	Urotrygonidae	*Urotrygon nana*	Dwarf round ray	CR
Coastal	Urotrygonidae	*Urotrygon reticulata*	Reticulate round ray	NT
Coastal	Urotrygonidae	*Urotrygon rogersi*	Roger's round ray	VU
Coastal	Urotrygonidae	*Urotrygon simulatrix*	Fake round ray	DD
Coastal, Shelf	Rajidae	*Beringraja (Raja) cortezensis*	Cortez skate	NT
Coastal, Shelf	Carcharhinidae	*Carcharhinus porosus (cerdale)*	Smalltail shark	EN
Coastal, Shelf	Pentanchidae	*Cephaloscyllium ventriosum*	Swell shark	DD
Coastal, Shelf	Narcinidae	*Narcine vermiculata (vermiculatus)*	Vermiculate numbfish	LC
Coastal, Shelf	Rhinobatidae	*Pseudobatos prahli*	Gorgona guitarfish	NT
Coastal, Shelf	Arhynchobatidae	*Sympterygia brevicaudata*	Shorttail fanskate	NT
Coastal, Shelf	Carcharhinidae	*Triaenodon obesus*	Whitetip reef shark	EN
Coastal, Shelf	Urotrygonidae	*Urobatis pardalis*	Leopard round ray	NT
Coastal, Shelf	Urotrygonidae	*Urotrygon cimar*	Cimar round ray	NT
Coastal, Pelagic	Alopidae	*Alopias vulpinus*	Common thresher shark	VU
Coastal, Shelf, Pelagic	Carcharhinidae	*Carcharhinus albimarginatus*	Silvertip shark	VU
Coastal, Shelf, Pelagic	Dasyatidae	*Hypanus (Dasyatis) longus (longa)*	Longtail stingray	VU
Coastal, Shelf, Pelagic	Mobulidae	*Mobula birostris*	Giant manta	EN
Coastal, Shelf, Pelagic	Mobulidae	*Mobula tarapacana*	Sicklefin devil ray	EN
Coastal, Shelf, Pelagic	Mobulidae	*Mobula thurstoni*	Bentfin mobula	EN
Coastal, Shelf, Pelagic	Sphyrnidae	*Sphyrna mokarran*	Great hammerhead shark	CR
Coastal, Shelf, Pelagic, Bathyal	Lamnidae	*Carcharodon carcharias*	White shark	VU
Bathyal	Rajidae	*Dipturus ecuadoriensis*	Ecuador skate	DD
Bathyal	Arhynchobatidae	*Notoraja martinezi*	Barbedwire-tailed skate	LC
Bathyal	Rajidae	*Rajella eisenhardti*	Galapagos skate	LC

underpinning its vulnerability is essential for designing adaptive management strategies.

4.1 | Climate change factors affecting ETP chondrichthyans

A large fraction (>60%) of ETP chondrichthyans were rated with *high* exposure to climate change impacts. As described in the results, this reflects the widespread imprint of several climate change factors (ocean warming, acidification, and changing oxygen levels), and the large number of coastal species that are exposed to additional potential stressors from salinity and sea level changes. It should be recognized, however, that the climate change factors used in this assessment differ in consensus on their projected changes and in the degree to which their impacts on chondrichthyans are understood (Table S1). The precautionary approach and resulting vulnerabilities derived herein did not attempt to deconstruct these differences, but we discuss them here.

Among the climate factors used for this assessment, ocean warming is distinguished by the high degree of certainty in its projected changes (Table S1), its biological effects that are relatively well understood, and its widespread imprint on the ETP. Projections of ocean warming in the ETP (Table S1) under a high emissions Representative Concentration Pathways (RCP) 8.5 scenario (IPCC, 2018) predict increases in the upper ocean (0–200 m) ocean temperatures of up to 3.6°C by 2100, with lesser but still significant trends at depth (200–600 and >600 m). While species' responses may vary, they frequently include shifts in their distributional range likely related to temperature changes affecting physiology and prey distribution (Chin et al., 2010; Hammerschlag et al., 2022). Such shifts have been reported for large wide-ranging chondrichthyans such as white sharks (*Carcharodon carcharias*) (Tanaka et al., 2021) and tiger sharks (*Galeocerdo cuvier*) (Birkmanis et al., 2020; Hammerschlag et al., 2022). Importantly, while

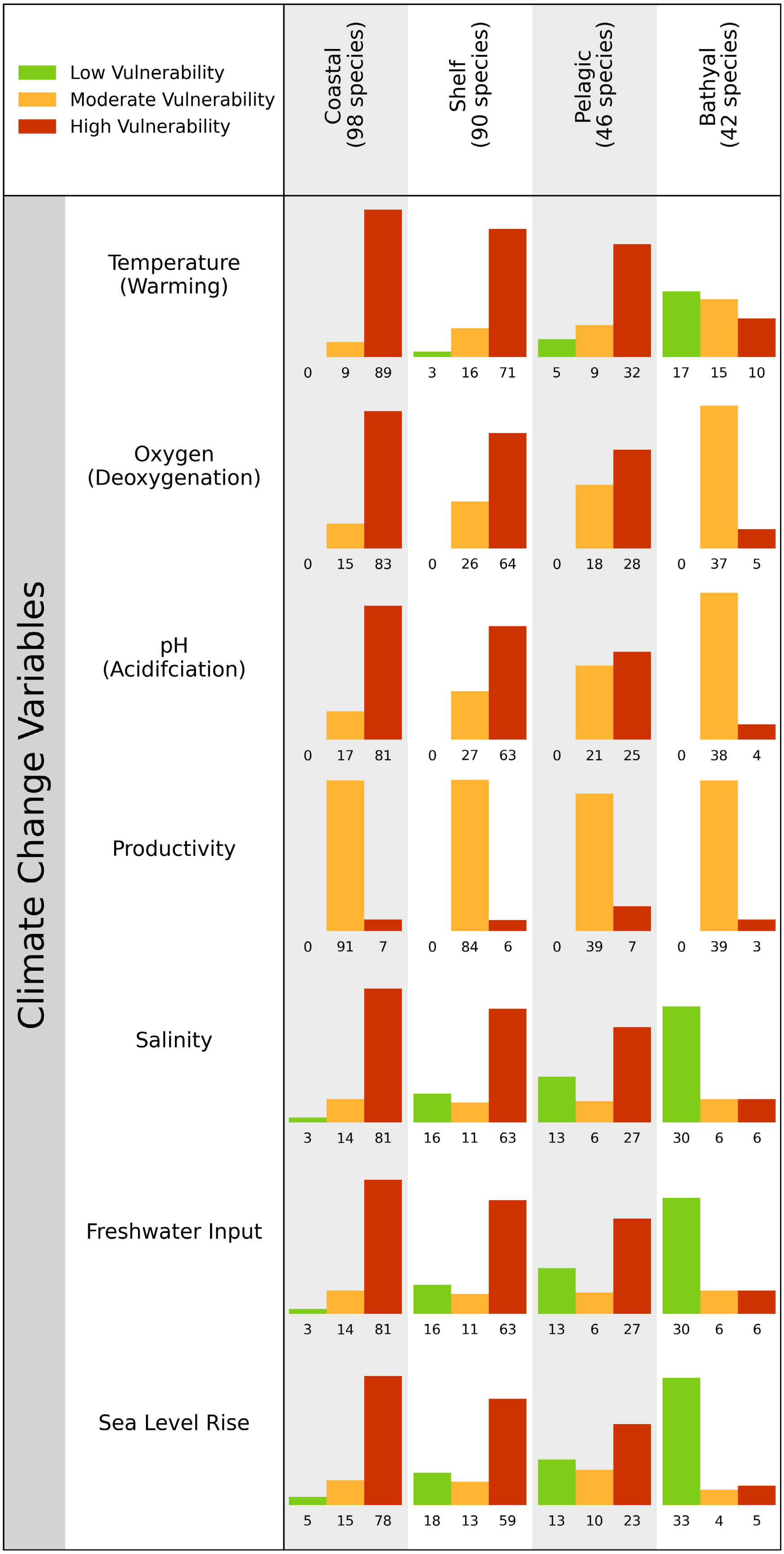

FIGURE 3 Vulnerability of Eastern Tropical Pacific chondrichthyan ecological groups to climate change factors (number of species on the *x*-axis).

some endothermic species like the white shark are able to regulate their internal body temperature and can accommodate a wide range of temperatures, changes beyond an optimal temperature range can compromise muscular, cardiac, and neural functions for other species (Nasby-Lucas et al., 2009; Ripley et al., 2021; Wheeler et al., 2020). Moreover, ocean warming may be making equatorial waters less

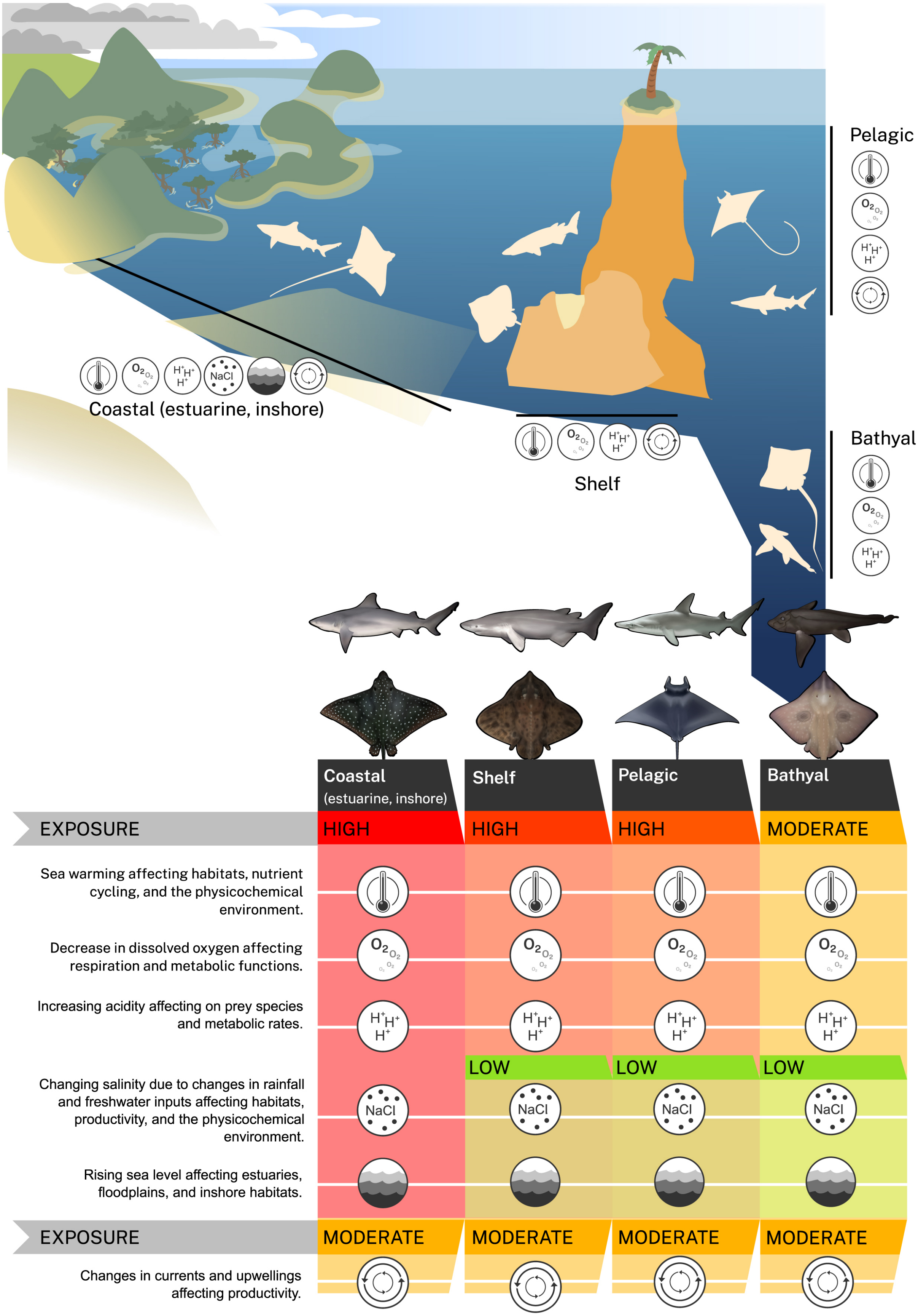

FIGURE 4 Exposure of Eastern Tropical Pacific chondrichthyans ecological groups to climate change factors.

suitable even for tropical and subtropical marine species already adapted to the relatively warm temperatures (Dale et al., 2022). Distribution shifts may be possible only for those species or life stages with high mobility, while species with limited mobility or those that rely on specific habitats may be more greatly impacted (Bangley et al., 2018). In the particular case of juvenile sharks and batoids restricted to coastal nursery habitats, changes in behavior to adapt to different conditions may reduce fitness, affecting the adult population viability for those species (Bouyoucos et al., 2022; Lear et al., 2019).

Similar to ocean temperature, there is broad agreement across ESMs also on ocean acidification trends (OA) over the next century and its impact on the ETP will be widespread in upper ocean layers. While the effects of OA on chondrichthyans are still poorly understood (Carrier et al., 2022), studies suggest impacts on the duration of embryonic development, hatching success, hunting behavior, food consumption, growth rates, locomotion, swimming activity, skeletal and denticle demineralization, and long-term survival (Carrier et al., 2022; Di Santo, 2015; Pistevos et al., 2015; Rosa et al., 2017; Vilmar & Di Santo, 2022; Wheeler et al., 2020). Additionally, such impacts can result in cascading effects on other species through different predator–prey relationships (Heithaus, 2001) as OA can also have impacts on critical habitats and food sources that rely on calcification such as coral reefs or shell-forming invertebrates (Hoegh-Guldberg et al., 2017; Hofmann et al., 2010). It is important to highlight that all studies on the effects of OA on chondrichthyan species to date are on benthic pump-breathing sharks and a small number of batoids (Rosa et al., 2017). Thus, there is a considerable lack of knowledge to predict the effects of OA or deoxygenation on ram-ventilating sharks, pelagic batoids, chimaeras, and deep-water species.

Dissolved oxygen differs from acidification because its impact on chondrichthyan physiology and habitats are relatively clear, although consensus on changes in future dissolved oxygen is limited. The ETP has the largest oxygen minimum zone (OMZ) in the world with prevalent hypoxia and anoxia conditions at near-surface and mid-water depths. This limits the vertical extent of pelagic species, thereby reducing the availability of suitable habitat (Abascal et al., 2011; Gilkinson et al., 2007; Vedor et al., 2021) which can considerably increase their exposure to surface fisheries (Prince & Goodyear, 2006; Vedor et al., 2021). Hypoxia, especially in combination with ocean warming and/or OA, can influence respiratory rates and ventilator repression, reduce activity and metabolic rates, and limit the vertical extent of migrations (Carrier et al., 2022; Prince & Goodyear, 2006; Sampaio et al., 2021; Vedor et al., 2021). Despite uncertainties about OMZ expansions, the prevalence of hypoxic and anoxic conditions in the ETP and observational evidence of climate-driven dissolved oxygen changes underlies high exposure, particularly for those species relying on mid-water below the well-oxygenated surface layer. While deoxygenation seems to be the most overlooked factor in chondrichthyan physiology studies, particularly within a climate change context, negative physiological responses to deoxygenation are expected for all aerobic biota (Sampaio et al., 2021).

The combination of ocean warming, acidification, and deoxygenation are known to have compounding effects on species and ecosystems, thus it is becoming urgent to understand how marine organisms will respond to these drivers (Carrier et al., 2022; Di Santo, 2016). The potential of ETP chondrichthyans to survive local population-level extinctions resulting from these combined stressors may depend on their capacity to change their physiological responses and acclimatize at a similar timescale to the changes on these major environmental stressors (Carrier et al., 2022; Di Santo, 2016).

Unlike most risk assessments, we have included changes in primary productivity in our analysis. While the literature suggests that low latitude areas such as the ETP may experience a decline in productivity with ongoing climate change (Doney, 2006), considerable disagreement between model projections remain (Bopp et al., 2013; Kwiatkowski et al., 2020) and the mechanisms and relationships driving these projections have been left unresolved by many ESMs. Importantly, while primary production provides the foundation for marine foodwebs, the relationship between primary production and higher trophic level productivity can be complex (Friedland et al., 2012; Stock et al., 2017). However, projections of climate change impact on fisheries suggest that primary productivity changes may be amplified at higher trophic levels (Lotze et al., 2019). In this assessment, limited consensus on the directionality and magnitude of the expected changes led to *moderate* exposure ratings for all but the most plankton-dependent species. Further research is required to better understand primary productivity changes (e.g., Kwiatkowski et al., 2020) and to comprehend the sensitivity of chondrichthyans' trophic dynamic.

Finally, the exposure of coastal environments to changes in sea level and freshwater inputs/salinity, were a primary factor contributing to the overall *high* vulnerability of coastal species. While there is considerable uncertainty surrounding the magnitude of sea level rise, particularly associated with ice sheet responses, increases in global mean sea level are projected over multiple RCPs and time horizons, with end-of-21st century RCP8.5 projections ranging from 0.61–1.10 m at medium confidence level (Oppenheimer et al., 2019). Freshwater changes generally reflect robust patterns of increased precipitation near the equator and decreases in subtropical zones (i.e., the wet get wetter and the dry get drier, Feng & Zhang, 2015). As it will be discussed in the next section, the potential impacts of these changes on coastal species and those that use coastal and estuarine areas as nurseries are numerous, though not well understood.

4.2 | Vulnerability of ecological groups to climate change

4.2.1 | Coastal species at high risk

This assessment found that the majority of *highly* vulnerability chondrichthyans were coastal species (Figure 2d). As discussed above, these species have high exposure to large and broad changes such as ocean warming, deoxygenation, and acidification, in addition to coastal-related factors such as sea level rise and changes in salinity. In particular, shallow coastal habitats are expected to be frequently exposed to extreme events (e.g., hurricanes), which will further increase the thermal stress in these environments (Cabral et al., 2019). The ETP coastline topology of habitats includes mangroves, which function as nurseries for many species of chondrichthyans (Llerena et al., 2015; López-Angarita, Villate-Moreno, et al., 2021; Zanella et al., 2019). However, mangroves are expected to be greatly impacted by climate change-related physical processes in the future due to projections of high incidence of tropical storms, areas of high relative sea level rise, and increases in precipitation (Cabral et al., 2019; Ward et al., 2016).

Panama and Colombia have some of the highest rates of annual rainfall in the world, maintaining many river deltas and estuaries with low salinities (Fiedler & Talley, 2006; López-Angarita, Cubillos-M, et al., 2021), yet Central America is one of the regions where climate change models consistently predict increases in temperature and decreases in precipitation during the wet season (Ward et al., 2016). These changes will alter estuaries and lagoons, with some potentially becoming incorporated into the sea. If coastal development allows it, the emergence of new estuarine zones will appear upstream, with different salinity as freshwater inputs change with increases in upstream rainfall (Martínez-Arroyo et al., 2011). Within the coastal ecological group, there are a few species that may tolerate various levels of salinity (e.g., *C. leucas*) (Martin, 2005). While elasmobranchs' euryhalinity is not yet well understood, studies suggest that this group may have larger tolerance than thought (Wosnick & Freire, 2013), which may confer a level of adaptability when freshwater inputs change.

Importantly, 66% of ETP chondrichthyans use coastal nurseries, and 23% of these species were also found to have *high* vulnerability to climate change. Thus, identifying and protecting key coastal habitats would be critical to inform habitat-focused actions. Moreover, improving our understanding of how reliant ETP chondrichthyans may be to threatened mangrove, coastal, and estuarine habitats during their early-life development would also help to maintain species' resilience to climate change impacts.

4.2.2 | Shelf and pelagic ecological groups

Pelagic and shelf ETP chondrichthyans had an overall *moderate* vulnerability to climate change although many species rely on coastal nursery areas, which increased their vulnerability ranking. In addition to exposure to ocean warming, acidification, and potential oxygen changes, shelf and pelagic ETP chondrichthyans are likely to be affected by changing currents that alter upwelling patterns and nutrient cycling (Fernández-Álamo & Färber-Lorda, 2006). However, some species of pelagic and migratory chondrichthyans may be able to move across different gradients of temperature, dissolved oxygen, and pH and accommodate changing conditions, which led to a *lower* Rigidity ranking (higher adaptability) and an overall *lower* vulnerability.

We note that a number of pelagic sharks that were rated with *moderate* vulnerability in this study were ranked with *low* vulnerability in another recent study in adjacent waters (e.g., McClure et al., 2023). This difference reflects the nature of vulnerability assessments as McClure et al. considered a range of fish groups that includes some extremely long-lived anadromous and rare rockfish species. Pelagic sharks may seem less vulnerable, when viewed relative to this wider range of species. It is important to highlight that the aim of the current study was to assess the vulnerability within the group of chondrichthyans in the ETP. Additionally, the consideration of potentially consequential changes in primary productivity elevated the vulnerability of pelagic species from *low* to *moderate* levels.

Many shelf and pelagic chondrichthyans forage in nutrient-rich oceanic upwelling areas, which may shift location, changes in its strength, or become less predictable (Rykaczewski et al., 2015; Sydeman et al., 2014). Phytoplankton abundance and biogeochemical patterns, including hypoxia, can result in large-scale shifts in their distribution (Hays et al., 2005), affecting the distribution, abundance, and seasonality of plankton (Robinson et al., 2009). Planktivorous ETP chondrichthyans (devil rays, whale and basking sharks) could face major challenges if changes in wind and ocean currents that alter the frontal zones and upwellings and create high-density patches in tropical waters (Cabral et al., 2023; Fernández-Álamo & Färber-Lorda, 2006; Lezama-Ochoa et al., 2019). Furthermore, the ENSO phenomenon, can alter upwelling events and their seasonality, affecting reef fish composition and ecosystem function (Eisele et al., 2021; Skubel et al., 2018; White et al., 2019).

4.2.3 | Bathyal ecological group

In this assessment, only 13 species were present exclusively in the Bathyal ecological group (four sharks, seven rays, and two chimaeras) and it had an overall *moderate* vulnerability to climate change. Only four species had *high* vulnerability to climate change likely because the depth of bathyal habitats provide partial refuge from some climate change signals (e.g., attenuated warming and acidification). While the projected changes in sea temperature, dissolved oxygen, and pH at >500 m depth in this study were minor relative to changes in shallower waters, three bathyal endemic skates (*Dipturus ecuadoriensis*, *Notoraja martinezi*, *Rajella eisenhardti*) that are known to occur in specific locations within the ETP had an overall *high* vulnerability to climate change. A *high* ranking in *sensitivity* and *rigidity*, suggests that these species may be most sensitive to even minimal habitat changes.

Recent advances in technology for marine exploration have increased our knowledge of deep-sea chondrichthyans in the ETP (Buglass et al., 2020; Cerutti-Pereyra et al., 2018; Friedlander et al., 2019), although there is an important lack of data for most deep-sea chondrichthyans (Finucci et al., 2021), which limits our understanding of climate change impacts on such species and ecosystems. Additionally, the impacts of climate change on the deep ocean have received little attention compared to coastal and pelagic ecosystems (Brito-Morales et al., 2020). Despite a lower vulnerability found for bathyal species compared to coastal species in this study, climate change is expected to change species ranges, decrease food availability, and reduce biodiversity (Doi et al., 2021; Levin et al., 2020), and projected rate of climate warming in the deep sea may exceed the rate at which deep-sea species are able to adapt to (Brito-Morales et al., 2020; Levin & Bris, 2015). Importantly, the deep sea and shallower ocean layers are connected through vertical movement of nutrients, and it is suspected that warming surface waters, increasing thermal stratification, and subsequent reduction of nutrient supply will reduce deep-sea productivity (Sweetman et al., 2017). Some bathyal regions of the world, such as the ETP, are predicted to face a 55% reduction of productivity by 2100, while the OMZ expansion in parts of the ETP is projected to exceed physiological limits of many species leading to reduced biodiversity resulting in a cascade of effects at depths over 500 m (Sweetman et al., 2017). Deep-sea chondrichthyans cannot be ignored given their limited ability to recover from overexploitation as they are highly sensitive to fishing pressure (Georgeson et al., 2020; Simpfendorfer & Kyne, 2009) and climate change may further increase their susceptibility to human-induced pressure.

4.3 | Special cases

4.3.1 | Batoids—endangered and understudied

This assessment found that 73% of ETP chondrichthyan species with *high* vulnerability to climate change were batoids, although a considerable knowledge gap still exists for this subgroup, which hampers management and conservation efforts. Importantly, six batoids species that had all three components ranked as *high* are rare within the ETP, mostly coastal, and have a high dependency on specific habitats. Specialization alongside rarity is a combination considered to increase extinction risk and vulnerability to climate change, thus species that are ecologically dependent on specific habitats are more susceptible than those that can use different habitat types (Chin et al., 2010; Davies et al., 2004).

Five batoids with *high* overall vulnerability to climate change are also considered EN or CR by the IUCN Red List (*Pristis pristis* (CR), *Urotrygon reticulate* (CR), *Mobula birostris* (EN), *M. tarapacana* (EN), *and M. thurstoni* (EN); Table 3). The higher numbers of batoids with *high* vulnerability to climate change found in this study highlights a critical need to include this group in management efforts throughout the region while also stressing the lack of information. Importantly, many batoid species sustain fisheries (Croll et al., 2016; Cuevas-Zimbrón et al., 2011; Dulvy et al., 2000; Kyne et al., 2020; Tamini et al., 2006) and some species have replaced sharks in coastal fisheries where sharks or other resources have been depleted (Bizzarro et al., 2009; Feitosa et al., 2021). While some batoids such as mantas, sawfishes, wedgefishes, and guitarfishes have been included in international treaties to reduce their overexploitation, many other batoids species are also vulnerable to overexploitation and climate change and require management and conservation planning that integrates such vulnerability.

4.3.2 | Highly migratory and iconic species

The ETP is home to several highly migratory chondrichthyan species that are also iconic for marine tourism in the ETP (Eckert & Stewart, 2001; Ketchum et al., 2014; Lara-Lizardi et al., 2020). Three out of five species of devil rays (*Mobula birostris*, *M. tarapacana*, *M. thurstoni*) and one out of six species of hammerhead sharks (*Sphyrna mokarran*) occurring in the ETP were found to have *high* vulnerability to climate change in this assessment, while whale sharks (*Rhincodon typus*) had a *moderate* vulnerability.

While the capacity of migratory species to move across gradients of environmental cues may confer adaptability and potentially enable them to adjust to new conditions, highly migratory species have complex migration patterns and depend on the availability of suitable habitat in many locations. The *high* vulnerability of highly migratory species to climate change found in this study highlights the many threats that these species face as they encounter multiple pressures throughout their range, leading to cumulative and synergistic impacts over their lifespan (Robinson et al., 2009). Additionally, changes in frequency, abundance, route, or timing of migrations and aggregations of these species may have substantial economic consequences for the marine-based tourism they sustain in the ETP and the efficacy of marine protected areas.

4.4 | Caution due to uncertainty and low confidence

Of the 132 ETP chondrichthyan species assessed, 12% ($n = 16$) had low confidence because ≥50% of the information used for the assessment was sourced from a sister species, thus, the assessments of those 16 species should be considered as preliminary. Notably, half of those 16 species were batoids, all species with the combination of *high* vulnerability and low confidence were also batoids, and 62% of species with low confidence were bathyal species (Table S5). These results suggest an important lack of information about batoids and bathyal chondrichthyans in the ETP (Chin et al., 2010; Finucci et al., 2021).

The assessment framework used in this study accommodates a range of data types and various levels of uncertainty (Chin et al., 2010; Georgeson et al., 2020; Hare et al., 2016). The framework's logic structure is fundamentally precautionary as all three components for all climate change factors are unlikely to be ranked as *high*. While there should be caution in using the assessment for those 16 species with low confidence, it integrates the best available information in a systematic process with experts' judgment, thus representing an important first step in examining climate change risks to these relatively data-poor species.

4.5 | Synergies with other anthropogenic pressures

Understanding the cumulative effects of climate change in combination with other stressors affecting chondrichthyans and their ecosystems is crucial for adaptive management. Human impacts are higher in coastal zones than offshore areas, with fishing, climate change, habitat destruction, and pollution being identified as the most significant pressures (Cabral et al., 2019). Overfishing, however, is the most pervasive threat to chondrichthyans globally, placing this group as one of the most threatened marine groups due to overexploitation (Dulvy et al., 2014, 2021; Field et al., 2010; Pacoureau et al., 2021). Pelagic species such as silky sharks (*C. falciformis*) and devil rays (Mobulidae) already experienced a considerable reduction in abundance in the ETP (Croll et al., 2016; Villate-Moreno et al., 2022). Climate change projections indicate decreases in suitable habitat for species caught in pelagic fisheries in the ETP, the movement of invasive species from tropical to temperate waters, and an increase in local losses in abundance along the ETP platform due to climate change (Clarke et al., 2021). Areas identified as having more at-risk species to climate change tend to be located in tropical and subtropical oceans, and the combination of climate change and fishing pressure will potentially result in high conservation risk for exploited chondrichthyans targeted in the region (Cheung et al., 2018; Vedor et al., 2021).

Human activities on land have also affected coastal habitats through urbanization, agriculture, and aquaculture. Second to overfishing, severe coastal and estuarine habitat loss and degradation, alongside land-based sources of pollution, have been highlighted as a significant global threat faced by sharks and rays (Dulvy et al., 2014, 2021; Jorgensen et al., 2022). The cumulative effects of exploitation, pollution, and habitat degradation can exacerbate a species' vulnerability to climate change, particularly in estuarine ecosystems that are disproportionally affected by coastal development (Pratchett et al., 2011). In extreme cases, some endemic, threatened, or rare chondrichthyan species may be eliminated from the ETP if they are unable to adapt to the cumulative effects of coastal fisheries, habitat degradation, and climate change.

5 | CONCLUSIONS AND RECOMMENDATIONS

This risk assessment provided a systematic evaluation of the vulnerability of 132 chondrichthyans to climate change in the ETP and showed that coastal chondrichthyans in the ETP are at highest risk to climate change. By understanding species' vulnerabilities and synergies with other risk factors, research and management can be focused on species and areas that are most vulnerable to multiple stressors.

The information produced in this assessment can be used by managers to inform fishery and spatial management plans, guide the inclusion of climate variables in species and ecosystem models, and identify species-specific research and management needs. Reducing the impacts of climate change will require a variety of spatially- and non-spatially fixed approaches. For example, coastal habitats that sustain species and species groups at high risk must be protected to maximize their resilience. In the ETP, this means prioritizing protecting mangroves, estuaries, catchments, and intertidal areas from common threats such as coastal urbanization, disruption of water flow, eutrophication, and pollution. Research to resolve the considerable uncertainties surrounding the tolerance of chondrichthyans to climate change is critical for such measures to be effective. Additional pressures, such as fishing, must also be addressed to minimize threats and alterations in species distributions and seasonal cycles resulting from climate change that can lead to changing reference points for management, which can in turn influence management planning. Unfortunately, the understanding of climate change impacts on fisheries management and coastal planning in the ETP is still lacking, as well as policies that support responses or opportunities to finance climate change mitigation measures. To ensure long-term sustainability of chondrichthyans in the ETP, it is crucial to identify and include important stressors into management. High-risk species should be considered for specific conservation actions, and both fisheries management plans and risk assessments should focus on such species to assess sustainability and guide management.

Ocean warming should be included in regional scientific advice and management. For example, thermal performance regimes (Lear et al., 2019) can be used to predict potential changes in migration patterns and predict the temperatures that may trigger shifts in behavioral patterns in species associated with specific habitats (e.g., nurseries). Using climate models to project key species' habitats and mapping their movements into the future could also help understanding the extent of shift ranges (Diaz-Carballido et al., 2022) and interactions with fisheries fleets to inform management policies (Dale et al., 2022).

This assessment also highlights the need for further research to understand those species highly vulnerable to climate change and research should focus on filling in knowledge gaps that can directly guide management. The links between population dynamics and habitat preservation and restoration should be further investigated as preserving these key habitats in the ETP that will contribute to protecting already threatened chondrichthyans species. An international commitment to long-term support for regional monitoring and research programs is crucial to identify areas where action is required and to monitor the effectiveness of management actions. Lastly, reducing anthropogenic climate driving and minimizing greenhouse emissions through internationally co-ordinated and basin-wide strategies in particular key habitats and along migratory corridors will prove beneficial for reducing the vulnerability of chondrichthyans species in the ETP.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are openly available in Zenondo at https://doi.org/10.5281/zenodo.11218757 and https://doi.org/10.5281/zenodo.11278035.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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